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Semi-Annual Progress Report, June 1 - Nov. 30, 1965, and
Proposal for Continuation of Research, June 1, 1966 - May 31, 1967

on

EXPERIMENTAL AND ANALYTICAL STUDIES
OF
PLASMA TRANSPORT PROPERTIES

Submitted to the
National Aeronautics and Space Administration
Washington, D. C. 20546

by the
Department of Aeronautics and Astronautics
Stanford University
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NASA Grant NGR 05-020-091

Daniel Bershader
Principal Investigator

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ABSTRACT

A short report is given herein of progress during the first six-month period of work supported by the referenced NASA grant. The effort has included theoretical studies of transport coefficients of ionized gases, with and without equipartition of kinetic energy between electrons and heavy species. On the experimental side, design and construction of instrumentation have been largely completed, including some modifications of existing equipment, all for the purpose of the planned quantitative studies of the end and side-wall boundary layers. Also included is a proposal for continuation of the program for the year June 1, 1966 to May 31, 1967. The proposed work is substantially parallel to that suggested for the second year of the original two-year proposal submitted in November 1964[1].

CONTENTS

I. INTRODUCTION

The proposal of November 1964[1], which resulted in the award of the present NASA one-year grant, contained a two-year plan for research on transport properties. As indicated in this combined semi-annual progress report and proposal for continuation of the research program, progress so far has approximately followed the forecast. Thus, the continuation proposal, included in the last section of this report, is presented along the lines of the second-year plan in the original proposal.

The work performed to date can be divided conveniently into three areas. The first deals with the theoretical analysis of transport properties and is described in the section which follows. The next two areas are concerned, respectively, with studies of the end-wall boundary layer and the side-wall boundary layer. They are, in turn, treated in the two following sections.

Section V constitutes a brief technical discussion of the proposed continuation program, while the final sections deal with the personnel and budget for the continuation activity.

II. THEORETICAL ANALYSIS OF TRANSPORT PROPERTIES

The major analytical effort so far has been devoted to an examination of the transport property calculations for the two-temperature gas. The approach is based on the classical Chapman-Enskog-Burnett method of obtaining transport coefficients. Some of the results obtained to date have been reported at the recent San Francisco meeting of the Division of Plasma Physics of the American Physical Society[2]. It is worthwhile to summarize these results for they furnish perspective on the overall problem. In this method for solving for transport properties the distribution function (here we will treat only the electrons) f_e is written in the form $f_e = f_e^o(1+\varphi_e)$ where f_e^o turns out to be a Maxwellian distribution[3]. For the two-temperature gas the same assumption is made, but it is also assumed that the Maxwellian distribution has a temperature different from that of the heavy species. It is further assumed that terms of order $\left[(m_e/m_h)|T_e-T_h|/T_h\right]$ may be neglected in solving for φ_e . Based on these assumptions, complete expressions have been obtained for the thermal conductivity, electrical conductivity and diffusion coefficients of the electrons and heavy species. A noteworthy result is that the electron coefficients depend only on the electron temperature, and coefficients for the heavy species only on the gas temperature.

Approximate conditions under which the second assumption above is valid, have been obtained. One of these is

$$\frac{m_e}{m_h}\left|\frac{T_e - T_h}{T_h}\right| \ll \varphi_e$$

But basic to the Chapman-Enskog method is the assumption of small perturbation $\varphi_e \ll 1$. Hence, even though $m_e/m_h \ll 1$, it appears possible to have conditions in a gas under which this inequality is not met. Present work is directed towards retaining the first term of order $\left[(m_e/m_h)\,|T_e-T_h|/T_h\right]$ in the analysis.

Work has continued on the transport properties of equal temperature ionized gases. A paper giving the general theoretical expressions for computations of transport properties up to the fourth approximation (based mainly on work performed under another contract) has been submitted for publication. The expressions reported are quite complicated and tedious to use for other than simple mixtures. It is possible to make a large number of simplifications without much loss of accuracy in the coefficients. This has been done and the resultant expressions programmed for the B5500 computer. Comparisons are being made between the coefficients as computed with the simpler and exact expressions.

III. END-WALL BOUNDARY LAYER

Considerable effort has been expended in setting up the experiments in this region. Initial experiments with an end-wall plug showed a large amount of burning of the quartz windows in the test section. Since these windows must be flat within 1/4 wavelength for accurate interferograms, it is clear that such burning cannot be tolerated. The source of the burning was traced to the flow of the hot shocked gas past the plug-window interface into a large evacuated volume behind the plug. Considerable effort was expended in attempting to seal this passage, but it was finally decided to fabricate a new test section, which is presently in use. It differs from the previous section in that it provides for a much smaller gap between the windows and the end plug, and has an O-ring seal just after the windows. The first shots with this section showed considerably less window burning.

The last month has been devoted to setting up the interferometer, the light source, and rotating mirror camera, preparatory to taking streak interferograms of the gas behind the reflected shock. Some attention has been given to refinements in the light source, which utilizes the line and continuum radiation from an exploding tungsten wire. At present, the 20kV power source used to explode the wire is switched through a home-made air gap switch. This will be replaced in the near future by a commercial sealed switch, which should improve the reliability of the light source. At present, the light has a rise time of about 1 μs and a duration of about 300 μs. At the date of this report only minor optical adjustments were hindering us from taking interferograms of the shocked gas.

Associated with the experimental effort has been a critical analysis of the determination of thermal conductivity from the measured density profiles. In this connection, it should be mentioned that we have learned of very recent work in Germany[4] in which the very same technique was used to determine the thermal conductivity of air between 1140 and 6075°K. In this reference the thermal conductivity was adjusted in the solution of an approximate boundary layer equation so as to obtain agreement between the computed and measured density profiles. Our analysis will probe somewhat deeper and attempt to use the full boundary-layer equations. Consideration of the time scales of recombination and temperature equilibration indicates that most of the outer part of the boundary layer will be in chemical and thermodynamic equilibrium. If we assume that the region of nonequilibrium and the sheath near the wall have a small effect on the outer temperature profile, then we can use equilibrium boundary layer analysis to interpret the measurements. As a result, the equations can be reduced to an ordinary differential equation by means of a similarity transformation, and we can work with the total, i.e., reactive plus translational thermal conductivity. For the present we plan to confine our experiments to the un-ionized regime, so as to demonstrate the feasibility of the method. Shock strength will be increased later.

IV. SIDE-WALL BOUNDARY LAYER

Studies in this area are directed towards comparison of predicted and measured density profiles using accurate computations of transport properties. A suitable treatment of the problem must take into account several phenomena -- the finite electron-ion recombination rate, the ambipolar and thermal diffusion, the radiation and the thermal non-equilibrium between the electrons and the heavy species. Few investigators have analyzed this problem in detail, most work being exclusively of a theoretical nature, and then only in some simple limit, i.e., weakly ionized gas.

The structure of the boundary layer has been studied analytically in some detail. It has been found that the gas will be in thermal and chemical equilibrium only in regions close to the unperturbed plasma. A numerical program for obtaining the variation of properties across this boundary layer is currently under development. Hopefully, this program will furnish electron and mass density profiles for comparison with experiments.

The experiments will be made with a new quantitative schlieren device which may be a useful alternative to the interferometer for measuring low-level electron densities in the boundary layer. A similar device has been used elsewhere with considerable success in measuring electron density profiles in the theta-pinch[5]. As used here, the method will employ two inclined slits with light at two wavelengths. Photographs will give continuous records of the electron and mass densities through much of the boundary layer. This camera has been designed and is currently in an initial testing stage.

V. PROPOSAL FOR CONTINUATION OF RESEARCH PROGRAM,
June 1, 1966 - May 31, 1967

1. Theoretical Studies

It is proposed that the theoretical studies be continued on several areas. Which of these will be emphasized will depend on progress during the present period and the tractability of the problems.

(a) Two-temperature gas: As indicated in Section II, substantial progress has been made in obtaining expressions for the transport coefficients for this mixture. Work would be directed toward reducing the number of assumptions used in the present formulation. Any reduction of such assumptions would, of course, result in a more rigorous theory for the properties.

(b) Approximate expressions for the transport coefficients: The kinetic theory expressions for the transport coefficients are cumbersome to use for computing the properties of real gases. As a result, various approximate mixture rules have been developed, both for the un-ionized gas and, lately, for the ionized gas. It is apparent from our work that the usual rules are not sufficiently accurate in the ionized gases. Some effort has already been expended in obtaining simplifications of the theoretical expressions, and this work would be continued.

(c) Higher approximations to the viscosity: The viscosity has been treated thus far only to the second approximation in the case of the multi-component gas. We have found that there is an increase of 15% in going from the first to the second approximation to this coefficient in the fully-ionized gas. It would be worthwhile to examine the increase in the third approximation for the fully and partially ionized gases.

(d) Transport coefficients of real gases: As time permits, transport property computations would be extended to other gas mixtures. Currently under study are the properties of xenon and helium, but other gases, such as hydrogen or the alkalis, could be treated.

2. Experimental Program

It is proposed to continue the shock tube experiments in both the side and end-wall regions, with the view, as stated, of obtaining quantitative assessment of transport properties from measured boundary-layer profiles. By the end of this year's program we should have a number of interferograms available detailing the growth of the boundary layer on the end wall, when the gas is un-ionized or only partially so. These interferograms will be analyzed, as described in Section III, to check the thermal conductivity of argon at these lower temperatures. As experience is obtained with this method, the studies will be extended to include measurements in higher-temperature ionized argon.

Analysis of the interferograms at the end wall is dependent on the knowledge of the gas temperature at the outer edge of the boundary layer. At the lower Mach numbers, and away from the shock boundary-layer interaction "bubble", it has been rather well substantiated that conditions behind reflected shocks in monatomic gases can be predicted from careful measurements of incident shock velocity. With increasing shock Mach number, conditions behind the shock become less certain because of finite ionization rates and, in some cases, significant radiation losses from the ionized gas. Therefore, it is desirable to measure another thermodynamic variable in addition to the mass and electron densities available from two-wavelength interferograms. The quantity of most direct interest would be the temperature. Because of the well-known complexities associated with such measurements, attention will be focused, rather, on measuring the pressure in the end-wall region.

It is proposed to adapt, making modifications as required, a fast-rise-time end-wall gauge already employed for studies of relaxation phenomena not involving ionization[6,7]. This gauge was designed and used by Professor D. Baganoff, a recent addition to the Departmental faculty, who will supervise this phase of the work. The gauge has been shown to be completely free of overshoot and ringing during the measurement period, and produces a voltage output linear with applied pressure over a large pressure range. Typical accuracy is 3%.

As time permits, it is also proposed to use thin film gauges to measure the temperature history of the end and side-wall surfaces. With a standard analysis, it is possible to determine the heat flux to the wall. Such measurements can then be compared with predictions from boundary-layer analysis. Wall temperatures deduced from such measurements would serve as "anchor points" for measured boundary-layer temperature profiles.

REFERENCES

1. "Proposal for Research on Experimental and Analytical Studies of Plasma Transport Properties", Aero. No. 18-64, November 1964.

2. DeVoto, R. S., "Approximations for the Transport Properties of a Two-Temperature Ionized Gas", to be published in A.P.S. Bulletin.

3. Chapman, S., and Cowling, T. C., "The Mathematical Theory of Non-Uniform Gases", (Cambridge University Press, Cambridge, England, 1958).

4. Smeets, G., "Determination of the Thermal Conductivity of Hot Gases from the Temperature Boundary Layer in a Shock Tube", (in German), Z. Naturforsch. 20a, 683 (1965).

5. Lovberg, R. H., "Investigation of Current Sheet Microstructure", AIAA Paper 65-335, 1965.

6. Baganoff, D., "Pressure Gauge with One-Tenth Microsecond Risetime for Shock Reflection Studies", Rev. Sci. Instr. 35, 288 (1964).

7. Baganoff, D., "Experiments on the Wall-Pressure History in Shock-Reflection Processes", J. Fluid Mech. 23, 209 (1965).

VI. PERSONNEL

It is planned that the program will continue under the direct supervision of Professor Daniel Bershader as Principal Investigator. Dr. Donald Baganoff, a newly appointed Assistant Professor, is proposed as a second faculty investigator. Professor Baganoff came to Stanford from the California Institute of Technology where he made some outstanding contributions, both as a doctoral student and as a post-doctoral Research Associate, to the study of molecular relaxation processes in Professor Liepmann's large, low-density shock tube. He also was involved in the design and construction of another shock tube for the study of ionization processes. Brief reference to his part in the presently proposed program was made in Section V.

Professor I-Dee Chang will continue as a consultant to the program in the area of plasma flow theory. The program will not be charged for his services.

Dr. R. S. De Voto will continue as a post-doctoral Research Associate on the same basis as at present. Graduate students working toward the Ph.D. degree will serve as Research Assistants.

COGNIZANT PERSONNEL

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